Surface Integrity in Machining

J. Paulo Davim
Editor

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Preface

A surface can be defined as a border between a machined workpiece and its environment. The term surface integrity describes the state and attributes of a machined surface and its relationship to functional performance. In general, surface integrity can be divided into two aspects: first the external topography of surfaces (surface finish) and second, the microstructure, mechanical properties and residual stresses of the internal subsurface layer. For example, surface integrity is commonly defined as "the topographical, mechanical, chemical and metallurgical state of a machined surface and its relationship to functional performance". Performance characteristics that are usually sensitive to surface integrity include, for example, fatigue strength, fracture strength, corrosion rate, tribological behavior (friction, wear and lubrication, dimensional accuracy, etc.

This book aims to provide the fundamentals and the recent advances in the study of integrity surface in machining processes.

Chapter 1 of the book provides the definition of surface integrity and its importance in functional performance. Chapter 2 is dedicated to surface texture characterization and evaluation. Chapter 3 describes residual stresses and microstructure modification, as well as the mechanical properties in the subsurface layer. Chapter 4 contains information on characterization methods of surface integrity. Chapter 5 is dedicated to surface integrity of machined surfaces by traditional and nontraditional machining. Finally, Chapter 6 is dedicated to surface integrity of micro/nano-finished surfaces.

The present book can be used as a textbook for a final undergraduate engineering course or as a topic on manufacturing at the postgraduate level. Also, this book can serve as a useful reference for academics, manufacturing researchers, manufacturing, materials and mechanical engineers, professionals in machining and related industries. The interest of scientific in this book is evident for many important centers of the research, laboratories and universities throughout the world. Therefore, it is hoped this book will inspire and enthuse other researches in this field of science and technology

The editor acknowledges Springer for this opportunity and for their enthusiastic and professional support. Finally, I would like to thank all the chapter authors for their availability for this work.

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Surface Integrity – Definition and Importance in Functional Performance

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This chapter presents an overview of the nature of the surface that results from manufacturing processes, as this nature has long been recognized as having a significant impact on the product performance, longevity and reliability. Surface alterations may include mechanical, metallurgical, chemical and other changes. These changes, although confined to a small surface layer, may limit the component quality or may, in some cases, render the surface unacceptable. A basic understanding of the changes in the condition of the surface is very much required if improvement in product quality is to be attained. Surface integrity (SI) reveals the influence of surface properties and condition upon which materials are likely to perform. It has long been known that the method of surface finishing and the complex combination of surface roughness, residual stress, cold work, and even phase transformations strongly influence the service behavior of manufactured parts as fatigue and stress corrosion.

1.1 Introduction

All the varied modern technologies depend for the satisfactory functioning of their processes on special properties of some solids. Mainly, these properties are the bulk properties, but for an important group of phenomena these properties are the surface properties. This is especially true in wear-resistant components, as their surface must perform many engineering functions in a variety of complex environments. The behavior of material therefore greatly depends on the surface of the material, surface contact area and environment under which the material operates. To understand the surface properties and their influence on the performance of various components, units and machines, a branch of science called surface science has been developed.

A *surface* can be described in simple terms to be the outermost layer of an entity. An *interface* can be defined to be the transition layer between two or more entities that differ either chemically or physically or in both aspects. Hudson [1] defines a surface or interface to exist in any system that has a sudden change of system properties like density, crystal structure and orientation, chemical composition, and ferro- or para-magnetic ordering. Surfaces and interfaces can be examined closely using the high-resolution microscopy, physical and chemical methods available. For their realization, a great number of simple and highly sophisticated testing machines have been developed and used [2, 3]. These tools have been built by humans to sate their innate curiosity of surface and interface interaction phenomena.

Surface science can be defined as a branch of science dealing with any type and any level of surface and interface interactions between two or more entities. These interactions could be physical, chemical, electrical, mechanical, thermal, biological, geological, astronomical and maybe even emotional [4].

1.1.1 Historical

The birth of surface science could perhaps be attributed to the first few moments of the Big Bang with all the complex surface interactions following the birth of the Universe. Although the earliest known documented record of interest in physical surface phenomena are the inscriptions of the Babylonian cuneiform dating back to the time of Hammurabi (1758B.C.) which talk about a certain practice called *Babylonian Lecanomancy* [5], surfaces have had a bad reputation for a long time: they are – inherently – superficial, even diabolical;[1] they were considered deceptive and, therefore, morally suspicious. The Greek philosopher Democritus of Abdera believed that the essence of a thing is hidden in its interior, while the (misleading) sensate qualities are caused by the surface. It was not until the middle of the 19th century that a cautious acknowledgement of surfaces began: in art, literature, and the sciences. The intellectual prerequisite was to ascribe *positive* qualities to surfaces – in the widest sense. After this idea had been established, the progress of surface science, led by pioneers such as J.W. Gibbs (surface thermodynamics) and I. Langmuir (adsorption and thin films), was rapid.

In 1877, J. William Gibbs laid down the mathematical foundations for statistical mechanics and thermodynamics. In this effort he completely described the thermodynamics of surface phases [6]. Then came Irving Langmuir (Nobel Laureate in Chemistry, 1932) who made major contributions in the knowledge of surface phenomena and whose stupendous efforts led to the recognition of surface science as a significant research field [7]. He developed the first quantitative theory of adsorption in 1915 and also did research on oil films, lipids, biofilms and molecular

[1] As Wolfgang Pauli (1900–1958), a traditionalist, expressed it: “God made solids, but surfaces were the work of the Devil.” This very popular quotation exists in a great variety of versions.

monolayers while working in the laboratories of General Electric at Schenectady, N.Y. He also carried out fundamental research on work functions of metals and came out with a detailed model on thermionic emission. A comprehensive collection of his multidisciplinary research pursuits is found in the classic historical reference [8].

Surface physics was in a nascent stage after the discovery of the electron and the atom, and it wasn't until the 1960s that surface physics actually progressed to be an independent field. This was made possible by the ultra high-vacuum technology, newly developed sophisticated surface analysis tools and digital age computers that allowed for comparisons of actual theoretical calculations with available reliable experimental data.

Earlier events that had a direct impact on surface physics development were the work on thermionic emission by Irving Langmuir, the explanation of the photoelectric effect by Albert Einstein (Nobel Laureate in Physics, 1921) and the confirmation of De Broglies' assertion of the wave nature of quantum-mechanical particles through electron diffraction by Clinton Davisson and Lester Germer [7]. Davisson shared the Nobel Prize for Physics in 1937 with G.P. Thompson. The next two decades produced intensive theoretical research in this field.

The invention of the transistor in 1947 marked a milestone in the lineage of surface physics. Work in solid-state physics and semiconductors picked up pace after the war and since then surface physics has been moving along at a steady pace with new theories being put forward and contributions from several rewarding researchers.

The term *surface science* came into common use in the early 1960s. Although there had been many previous studies of surfaces and surface phenomena, some of which led to the Nobel prize winning work of Langmuir for his studies of absorption and of Davisson and Germer on the demonstration of low-energy electron diffraction, these studies were generally classified under various other scientific subdisciplines, such as physical chemistry or electron physics [9].

Since its inception, the field of surface science has undergone an explosive expansion. This expansion has been driven by the combination of the ready availability of ultrahigh-vacuum environments, the development of techniques for the preparation of microscopic single-crystal surfaces, and the application of an increasingly complex array of surface analytical techniques, which have made possible characterization of the structure and reactivity of a wide range of surfaces [7]. A classification of some of the important areas in the different fields of surface science is shown as an illustration in Figure 1.1.

Surface engineering is almost as old as structural materials used by men. From the beginnings of time until the early 1970s, mankind has worked on the development of surface engineering, although not aware of the concept [10]. Surface engineering provides one of the most important means of engineering product differentiation in terms of quality, performance and life-cycle cost. The term surface engineering has been in use for over 15 years. It may be defined as: The design of surface and substrate together as a functionally graded system to give a cost-effective performance enhancement of which neither is capable on its own. This is by definition a highly interdisciplinary activity (Figure 1.2). The successful implementation of surface engineering requires an integrated approach at the design

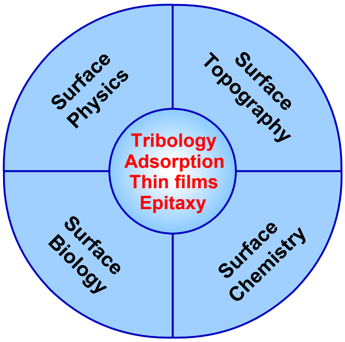

Figure 1.1. Important areas of surface science

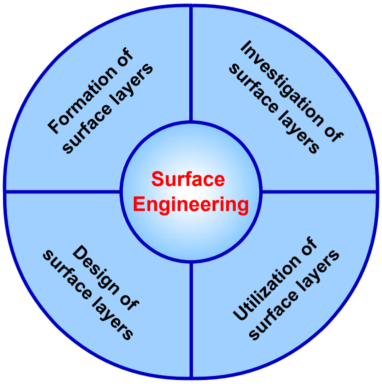

Figure 1.2. Important areas of surface engineering

stage, involving collaboration between design and surface engineers, as is increasingly being realized by managers in diverse industry sectors. In addition to being able to solve problems, surface engineering technologies have the ability to supply *added value* and thus add profit. The aim in surface engineering is to manipulate appropriate technologies to achieve optimal surface property designs for specific applications in the most cost-effective manner. Surface engineering thus has the ability to act as a bridge, transferring technology and expertise between end-user sectors that would not normally benefit from this cross-fertilization.

Surface engineering is a multidisciplinary activity intended to tailor the properties of the surface of engineering components so that their serviceability can be improved. The ASM Handbook defines surface engineering as "treatment of the surface and near-surface regions of a material to allow the surface to perform functions that are distinct from those functions demanded from the bulk of the material" [11]. Surface engineering aims to achieve desired properties or characteristics of surface-engineered components including:

- improved corrosion resistance through barrier or sacrificial protection;
- improved oxidation and/or sulfidation resistance;

- improved wear resistance;
- reduced friction energy losses;
- improved mechanical properties, for example, enhanced fatigue life, hardness or toughness;
- improved electronic or electrical properties;
- improved thermal insulation;
- improved biological properties;
- improved aesthetic appearance;
- and many others.

1.1.2 General Surface Considerations

An accurate description of the surface structures and especially surface composition of multicomponent systems is basic to the understanding of a variety of important surface phenomena. Such surface phenomena include heterogeneous catalysis, corrosion, adhesion, and lubrication. Also, electrical properties of interfaces can be greater influenced by compositions in the near-surface region.

A useful conceptual approach to the description of mixture surfaces is to model the energy of the system (e.g., an alloy) as if the components (e.g., atoms) of the system were connected by chemical bonds characteristic of the two species participating in the bond. This approach has been extremely successful in the development of solution thermodynamics of liquids and solids and has been called a quasichemical treatment [12] the term "quasichemical" leads to some confusion because it also has been applied to a specific type of non-random mixing model by Guggenheim (as presented by Graessley in [13]) as well as others. To avoid the ambiguity, the term "pairwise bond approach" is proposed to simplify a chemical description of interactions [12]. From this chemical description one can see why the mixture may experience the enrichment of at least one component in the surface region. The difference in bonding between like and unlike components in the mixture, and the absence of some bonds in the surface, result in a composition in the surface region different from the bulk composition.

Many surface-science-related publications discuss mainly the basic scientific properties of surfaces that are clean and in thermodynamic equilibrium, or nearly so. Many real surfaces that have been produced by machining are not smooth, and subjected to oxidation. All metals (except for gold and platinum metals) have stable oxides in air at room temperature. The surfaces of metal exposed to air are therefore oxidized, with the oxide layer growing at a rate determined by the diffusion of metal and oxygen atoms through the surface layer. When the surface is altered mechanically by machining, heavy plastic deformation of the surface layer occurs. During this deformation, oxide particles are forced under the surface and oxidized parts of the surface become covered with the displaced material. A mechanically produced surface therefore has a layer of a heavy disturbed mixture of metal and oxide on the outside, with a transition zone to the normal lattice below it.

Whereas the clean surfaces at high temperatures are (or approached) their equilibrium shape and are atomically smooth, the manufactured (machined) surface is still effectively immobile. A surface that is smooth in the technical sense will be very rough on the atomic scale. The surface roughness in this case is determined by the forming operation that was used to produce the surface.

When two reasonable clean and smooth metal surfaces are in atomic contact then interatomic forces across the area of contact give very strong adhesion causing formation a metallic junction. When a tangential force is applied to cause such surfaces in contact to slide over each other then either the junction is broken or the metal fails in shear a small distance away from the junction if the junction is stronger than the shear strength of either metal brought in contact.

A manufactured surface is not perfectly flat (round). As a result, the real contact area of two manufacturing surfaces in contact is normally much smaller that the apparent contact area, as these surfaces are contacted by their asperities. This results in the constancy of the friction coefficient of a pair of manufactured surfaces over a wide range of normal pressures. Due to the elastic deformation of the asperities, the actual contact area (and thus the friction force) increases with the normal pressure keeping the same friction coefficient as the ratio of the frictional and normal forces (stresses). Chemisorbed and adsorbed layers on a manufactured surface serve as a boundary-layer lubricant that significantly reduces the bonding forces in the contact.

1.1.3 Real Surfaces of Solids

The physics and chemistry of solids deal with an idealized surface, and thus are rarely concerned with real-world surface imperfectness. A real surface may look clean and polished, however, the surface microlayers, as shown in Figure 1.3, have been formed due to external factors including manufacturing, temperature action and oxide formation. Depending on the manufacturing process involved in producing a material, a zone of work-hardened material will occupy the base of these additional layers. Above this worked layer is an amorphous or microcrystalline

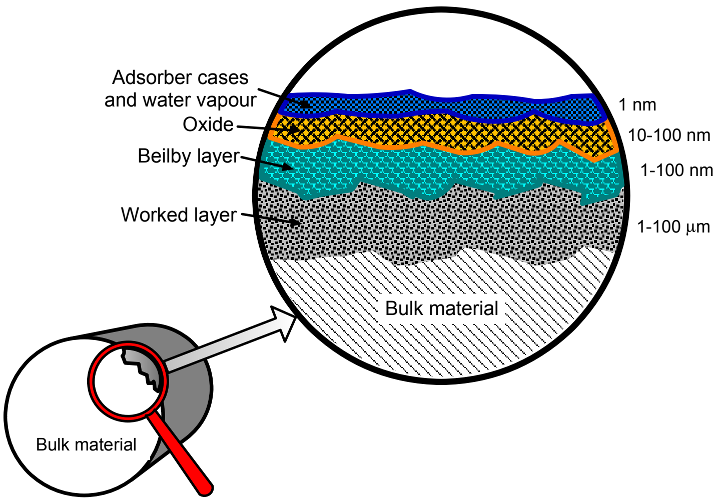

Figure 1.3. Schematic representation of a metal surface

structure, called the "Beilby" layer, which is a result of melting and surface flow during machining of the molecular layers [14]. An oxide layer sits on top of the Beilby layer, due to the oxygen available from the external environment, and surface oxidation mechanisms. A layer of adsorbents occupies the outer region and this is made up of water vapor or hydrocarbons from the environment that may have condensed and physically or chemically adsorbed onto the surface.

The surface structure may change in service. For example, microscopic investigation of surface layers on rails showed severe plastic deformation due to the normal pressure as well as shearing, together with a rapid change of temperature at service conditions lead to decomposition of the initial pearlite structure accompanied by surface oxidation, defect formation, carbon clustering, precipitation of nanosize carbide particles and austenitization of the material [15]. SEM study of fracture surfaces and fatigue crack initiation due to low-temperature irradiation showed that this radiation causes an increase in stress amplitude and a reduction in fatigue lifetime corresponding to radiation hardening and loss of ductility [16]. Neutron-irradiated samples showed a brittle fracture surface, and it was significant for large strain tests.

Other examples are: (a) environmental stress cracking of plastics by some chemical environments [17], (b) turbine vane and blade material surface deterioration caused by erosion [18], (c) surface corrosion [19], etc.

1.2 Surface Integrity: Known Notions

1.2.1 State-of-the-art

An excellent historical development of surface integrity (hereafter, SI) notion, as it is understood in manufacturing, was published by M'Saoubi *et al.* [20]. It is pointed out that the pioneering work of Field and his co-workers at Metcut (Cincinnati, OH, USA), through a series of publications, made a significant contribution to the subject setting the stage for future work [21–23]. They were indeed the first to introduce the concept of "SI" by means of defining the *inherent or enhanced condition of a surface produced in machining or other surface generation operation* [21]. Their subsequent comprehensive review of surface integrity issues that are encountered in machined components was among the first in the published literature [22], and this work emphasized the nature of metallurgical alterations occurring in the surface and subsurface layers of various alloys from conventional and non-conventional machining processes. Typical surface alterations were termed plastic deformation, microcracking, phase transformations, microhardness, tears and laps related to built-up edge formation, residual stress distribution, etc. They later provided a detailed description of measuring methods available for SI inspection [23], and presented an experimental procedure for assessing SI parameters. Their methodology specifies the use of three different levels of SI data sets to study and evaluate the characteristic features of machined surfaces (Table 1.1). Their ground-breaking achievements on the subject have contributed to a worldwide recognition and timeless value to this discipline leading to the subsequent establishment of an American National Standard on SI (ANSI B211.1, 1986).

Table 1.1. Different levels of surface integrity (SI) data set (source [23])

Minimum SI data set	**Standard SI data set**	**Extended SI data set**

Surface finish
Microstructure (10× or less
Microcracks
Macrocrack indications
Microstructure
  Microcracks
  Plastic deformation
  Phase transformation
  Intergranular attack
  Pits, tears, laps, protrusions
  Built-up edge
  Melted and re-deposited layers
  Selective etching
Microhardness
	Minimum SI data set
	Fatigue test (screening)
	Stress corrosion test
	Residual stress and distortion
		Standard SI data set
		Fatigue test (extended to obtain design data)
		Additional mechanical tests
		Tensile
		Stress rapture
		Creep
		Other specific tests (e.g., bearing performance, sliding friction evaluation, sealing properties of surface)

SI concerns not only the topological (geometric) aspects of surfaces but rather the whole assemblage of their physical, mechanical, metallurgical, chemical and biological properties and characteristics. Its objective is to assure the required service properties of surfaces in part and product manufacturing because many manufacturing operations directly affect these properties. For example, Figure 1.4 shows

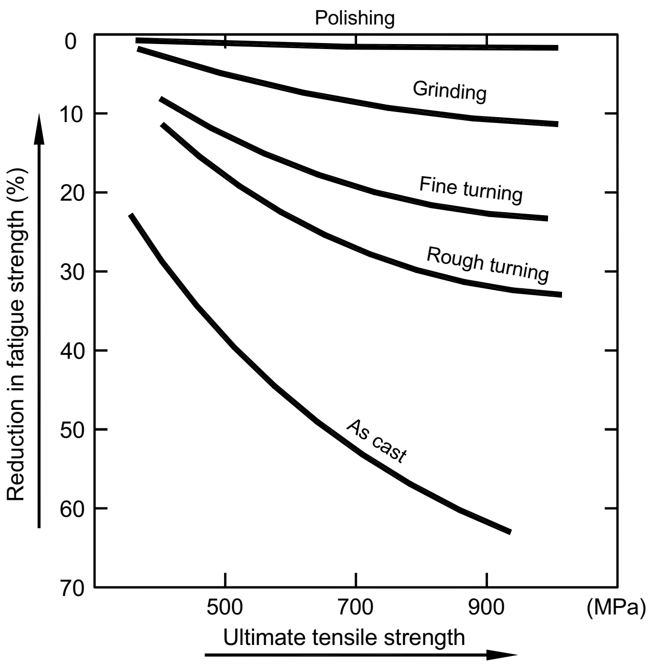

Figure 1.4. Reduction in fatigue strength of cast steel subjected to various surface-finishing operations

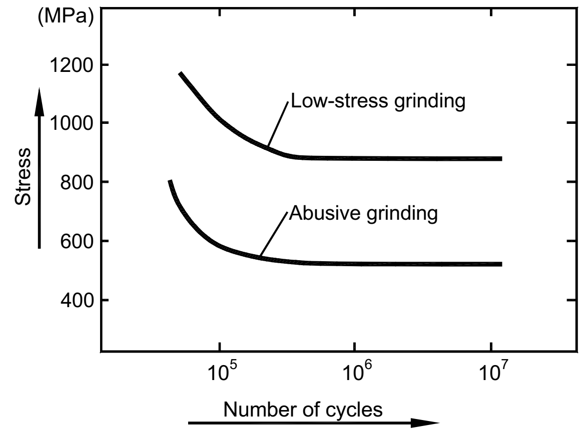

Figure 1.5. Showing that the location of the fatigue curve of ANSI 4340 steel quenched and tempered to HRC 51 depends on the mode of grinding

the influence of the surface-finishing operation on the fatigue strength of cast iron [24]. As seen, this strength depends on the particular machining operation chosen to finish the surface of a part as well as on the ultimate tensile strength of the work material. The rougher the surface, the greater the difference. The matter becomes more complicated when one realizes that SI depends not only on the chosen surface-finishing manufacturing operation but also to a great extent on the particular regime of this operation. To exemplify this point, Figure 1.5 shows the severe reduction in fatigue strength in grinding when an abusive regime is used [24]. Needless to say, SI depends on many system properties and characteristics of the entire machining system, which includes the tool and tool holder, spindle and prime drive, fixture and feed drives, coolant and method of coolant delivery, and many others that make the whole concept of SI in manufacturing rather complicated.

1.2.2 Some Typical Defects of the Machined Surface Affecting its SI

Various defects are caused by and produced during part manufacturing compromising SI. These defects can be classified as those of the original material and those imposed during manufacturing. Amongst many defects found in practice, the following are most common:

- Cracks are external or internal separations with sharp outlines. Cracks requiring a magnification of 10× or higher to be seen by a naked eye are called microcracks.
- Metallurgical transformation involves microstructural changes caused by temperature and high contact pressures. Included are phase transformations, re-crystallization, alloy depletion, decarburization, and molten and re-cast, re-solidified, or re-deposited material, as in electrical-discharge machining.
- Residual stresses caused by process forces, deformations and temperatures.
- Craters are shallow depressions.
- Inclusions are small, non-metallic elements or compounds in the metal.

- Intergranular attack is the weakening a grain boundary by liquid-metal embitterment or corrosion.
- Pits are shallow surface depressions, usually the result of chemical or physical attack.
- Plastic deformation is a severe surface deformation caused by high stresses due to friction or tool in manufacturing.

Visually distinguished microcracks are normally formed in the machining of brittle materials (Figure 1.6) or low-speed machining operations (Figure 1.7). This is because high temperature and pressure in machining of ductile materials causes healing of visible cracks. In service, however, such cracks may came to light as the strength of the healed bonds is smaller that that of the original material. Figure 1.8 shows a fatigue crack developed in the trunnion pin of an airplane. It originated in the root of the machining groove due to hidden pre-existed surface damage and was associated with shallow intergranular penetrations. Figure 1.9 shows a fretting crack developed from a grinding defect on a crankshaft shoulder.

Material-removal processes introduce structural changes to the surface of a workpiece. Severe plastic deformation of the machined surface occurs due to the action of the cutting forces and friction of the tool flank (Figure 1.10). This plastic deformation results in cold working of the surface layer. Hardness and tensile strength are increased with the degree of cold work, whilst ductility and impact values are lowered. The greater ductility of the work material, the deeper the cold-worked layer. Figure 1.11 shows a cold-worked layer formed in the turning of 304/304L stainless steel.

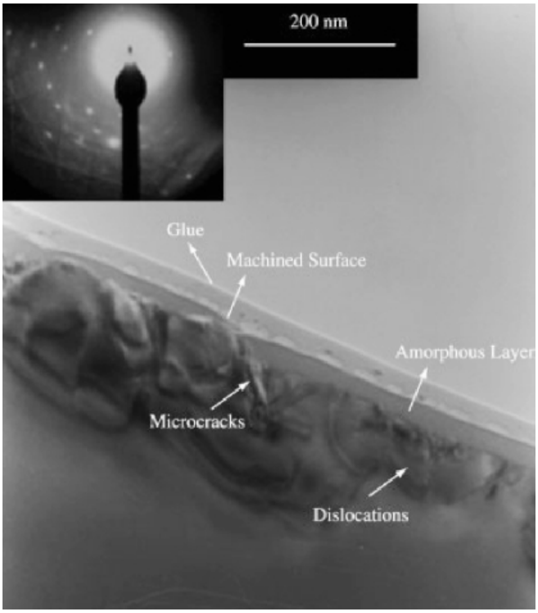

Figure 1.6. TEM cross-sectional image and diffraction pattern of a monocrystalline silicon sample turned with a single-point diamond tool

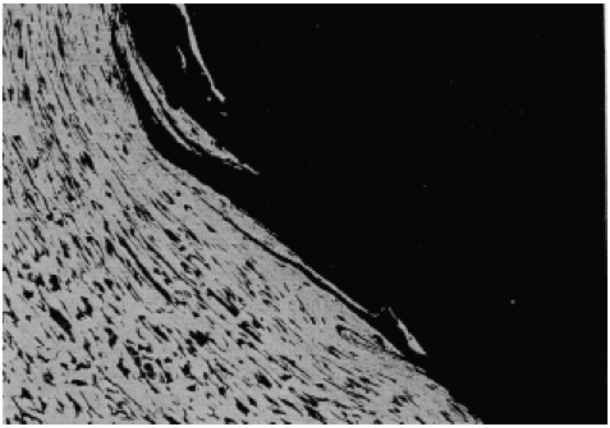

Figure 1.7. Micrograph of flaking found at the base of a thread in the fractured bolt (100×)

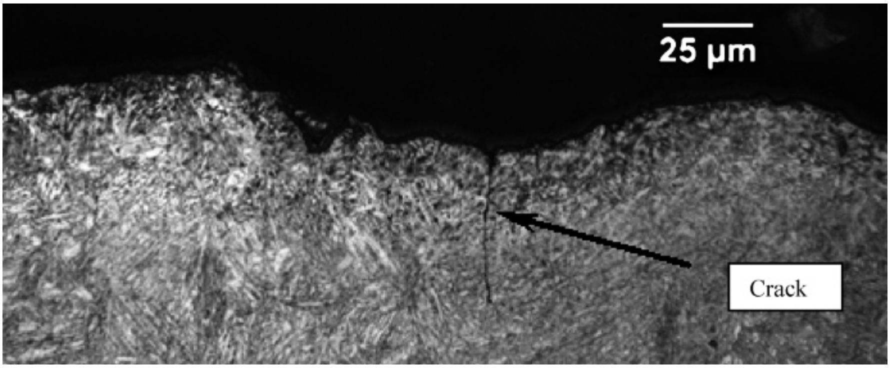

Figure 1.8. Fatigue crack indicated by arrow

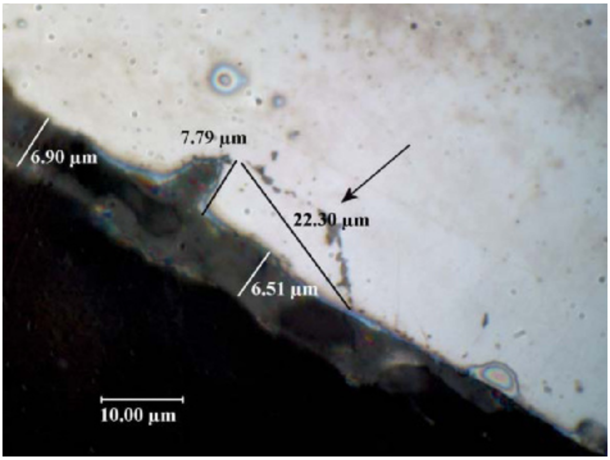

Figure 1.9. Fretting crack developed from a grinding defect on a crankshaft shoulder

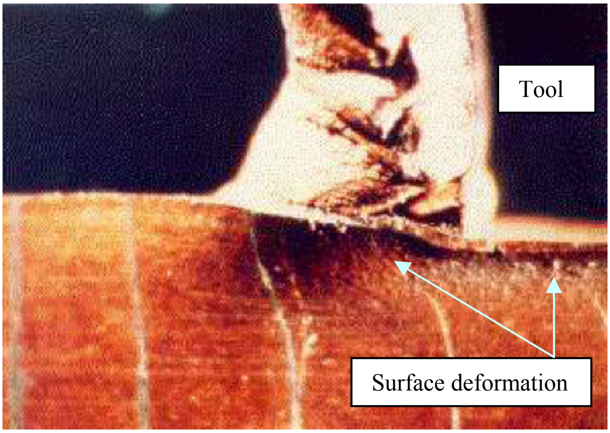

Figure 1.10. Surface plastic deformation in machining

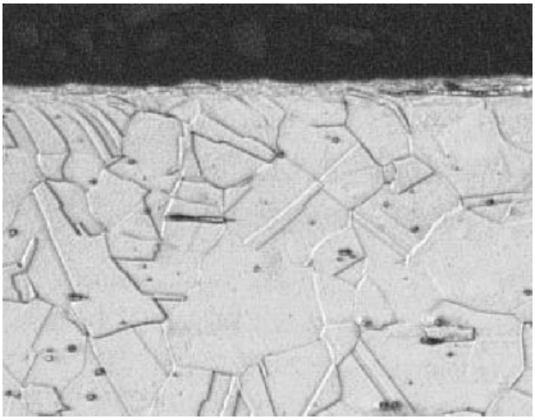

Figure 1.11. Microstructure showing deformation of grains at surface and otherwise normal microstructure of Type 304/304L stainless steel. (500×)

When hardened materials are machined, however, the surface modification may occur because of rapid thermal working, resulting in metallurgical transformation and possible chemical interactions. The worked surface can exhibit a vastly different structure compared to that of the bulk of the material. The white layers, metallurgical change and residual stresses are three basic facets of this layer [25].

The term "white layer" originated from the fact that these surfaces appear white under an optical microscope or featureless in a scanning electron microscope (SEM). Thus, in the literature, the term "white layer" is used as a generic phrase referring to very hard surface layers formed in ferrous materials under a variety of conditions, which appear white under the microscope [26]. Although the term "white layer" has become the customary way of referring to such layers, other terms such as white etching layer, non-etching layers, white phase, phase-transformed materials are also used [27].

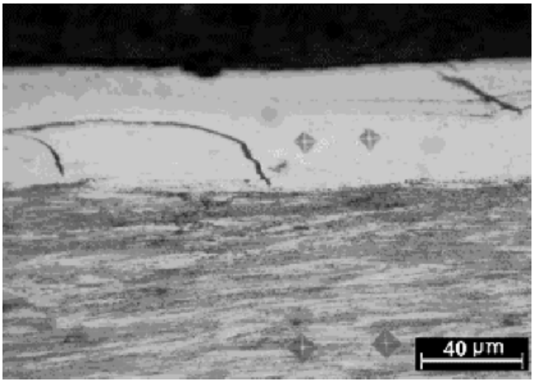

Figure 1.12. White layer formed in hard turning of ANSI 1065 steel

Perhaps the earliest mention of the presence of hard white layers on surfaces was in 1912 by Stead [28], who observed white etching layers on the surfaces of used steel wire ropes. He interpreted this as the formation of martensite as a result of frictional heating in service followed by quenching due to the colder sublayers. White layers in their different forms are as a result of factors attributed to the material removal process, such as thermal, mechanical or chemical unit events [27]. These can be directly related to factors such as strain, strain rate, heating rate, cooling rate and local environmental operating conditions. Figure 1.12 shows an example of the white layer.

Grinding requires a very large energy input per unit volume of material removed. The majority of this energy is converted to heat, which is concentrated in the surface layers of the material, within the grinding zone and as a result of this, a rapid rise in the localized temperature within the surface can occur. The actual rise in temperature depends on a range of factors, including the type of coolant, the method of coolant supply, the type of grinding wheel and the speed and depth of cut of the wheel. During grinding of hardened and tempered steel samples, the production rate, i.e., the stock removal rate, is limited by the increasing risk of thermal damage to the component. The severity of such damage, also known as grinding burns, depends on the temperature to which the workpiece surface was heated.

Figure 1.13 shows an extreme case of grinding burns on a high-speed steel hub rake face. Figure 1.14(a) shows an excessive wear of the hob rake face due to its low hardness (as seen in Figure 1.14(b)) caused by the grinding burns.

The problems caused by non-metallic inclusions and porosity are of major concern to cast iron and aluminum casting foundries and their customers in the automotive industry. The requirement to produce such castings economically, with reduced inclusions, is constantly growing. Micro inclusions can have a significant adverse effect on mechanical properties and may also impair machinability.

The yoke is a typical automotive part made of cast iron. Figure 1.15(a) and (b) show unmachined and machined yokes. Figure 1.15(b) shows a dark area on the machined surface on the cope side of the casting. The location was just below an exothermic riser. The initial thoughts were that the casting had not “cleaned-up”